Pre-Flight Tests with Astronauts, Flight & Ground Hardware, to Assure On-Orbit Success

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I. ABSTRACT

On-Orbit Constraints Test (OOCT's) refers to mating flight hardware together on the ground before they will be mated on-orbit or on the Lunar surface. The concept seems simple but it can be difficult to perform operations like this on the ground when the flight hardware is being designed to be mated on-orbit in a zero-g/vacuum environment of space or low-g/vacuum environment on the Lunar/Mars Surface. Also some of the items are manufactured years apart so how are mating tasks performed on these components if one piece is on-orbit/on Lunar/Mars surface before its mating piece is planned to be built. Both the Internal Vehicular Activity (IVA) and Extra-Vehicular Activity (EVA) OOCT's performed at Kennedy Space Center will be presented in this paper. Details include how OOCT's should mimic on-orbit/Lunar/Mars surface operational scenarios, a series of photographs will be shown that were taken during OOCT's performed on International Space Station (ISS) flight elements, lessons learned as a result of the OOCT's will be presented and the paper will conclude with possible applications to Moon and Mars Surface operations planned for the Constellation Program.

II. KEYWORDS

On-Orbit Constraints Test (OOCT), Fit checks, Test Aids, Flight Hardware, Ground Support Equipment, Internal Vehicular Activity (IVA), Extra-Vehicular Activity, Element (EVA).

III. INTRODUCTION

The Space Station Hardware Integration Office (SSHIO) was formed at Kennedy Space Center (KSC) to create an organization of personnel with flight hardware processing experience that would then go out into the field to provide assistance with the design and building of International Space Station (ISS) Elements. As part of the responsibilities SSHIO personnel were given existing ISS problems to solve or concerns to alleviate. One big concern of the Astronauts dealt with ISS Extra-Vehicular Activity (EVA) & Internal Vehicular Activity (IVA) hardware integration on-orbit, "Astronaut - How do we verify hardware built and launched on different missions will connect together in orbit?"

The On-Orbit Constraints Test (OOCT) concept was developed to alleviate the concern by combining Flight Hardware, flight hardware simulators called "Test Aids", Astronaut and ground processing personnel in a series of pre-launch tests performed during KSC ground processing on ISS Flight Hardware. Performing "Dry-runs" of the on-orbit EVA & IVA hardware/operations before launch, OOCT's included connecting cables, fluid umbilical & ducts that would test mating/demating, clocking, routing, etc. OOCT performed by Astronauts/rep with Mission personnel supporting, using Boeing Houston Procedure & Task leader with KSC National Aeronautics and Space Administration (NASA) signature authority. OOCT is a physical check of interfaces, not a functional check.

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IV. FIT CHECK & OOCT CONCEPT

The idea was very simple, fit check, which meant a physical mating/connection of flight hardware, the actual flight hardware together before being launched into space. Then for those flight items that have already been launched or could not be mating together while on the ground, create high fidelity simulators (called Test Aids) so any future/existing flight hardware would then have an OOCT performed to try and assure the both flight hardware pieces (the half already in space, its mating half still on the ground) would connect on orbit. One question that always came up was, "What does the OOCT verify that can't be verified by the fit check?" Below describes what is verified during both operations, followed by Fig. 1 – ISS fit check and OOCT concept:

      Fit Check verifies:
      Flight-to-flight mate
      Connector Clocking
      Connector to connector interference
      Connector to adjacent hardware
      Tool access
      Hand access
      Mating order of installation

      Additional data obtained from OOCT:
      Line length check
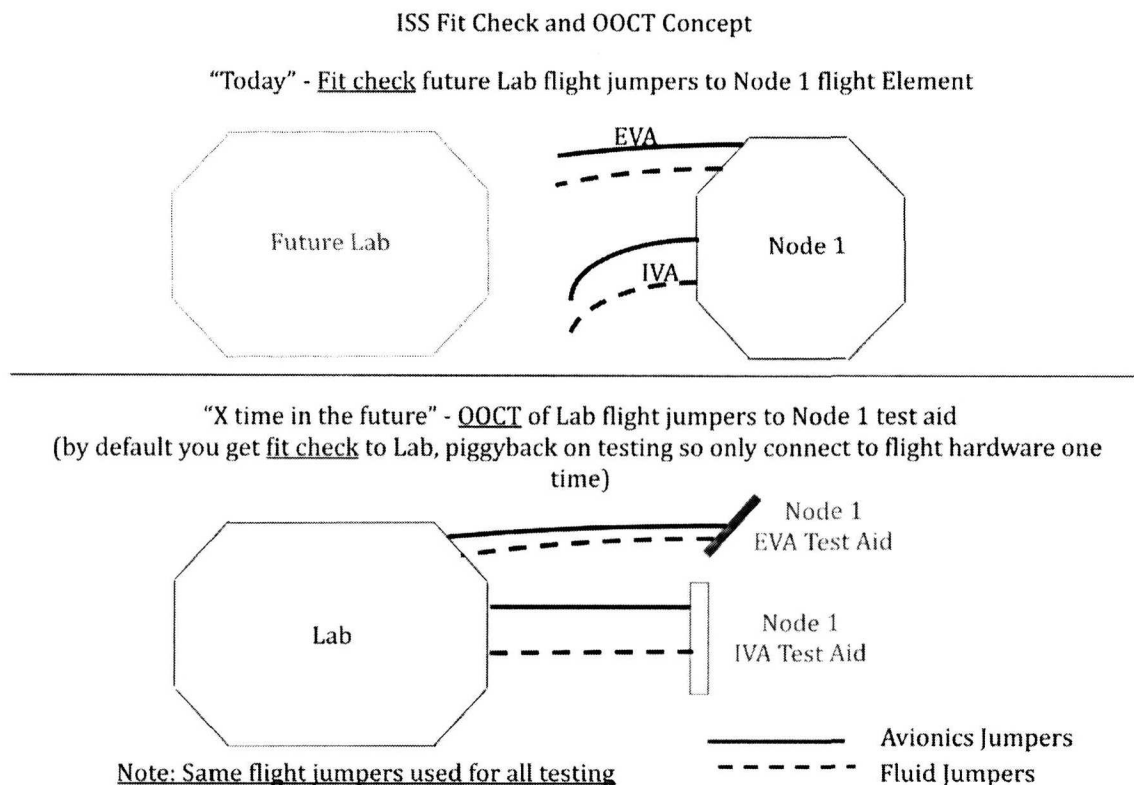   Cable clocking
      Routing obstructions

ISS Fit Check and OOCT Concept

"Today" - Fit check future Lab flight jumpers to Node 1 flight Element

"X time in the future" - OOCT of Lab flight jumpers to Node 1 test aid
(by default you get fit check to Lab, piggyback on testing so only connect to flight hardware one time)

Note: Same flight jumpers used for all testing

Figure 1. ISS fit check and OOCT concept.

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V. WHAT IS REQUIRED TO PERFORM SUCCESSFUL FIT CHECKS AND OOCT's

The on-orbit configuration(s) of the flight hardware is required to begin the OOCT process. There could be multiple on-orbit configurations, as was the case for the ISS Z1 Truss. An early on-orbit configuration has its deployable tray stowed when Z1 to Node 1 flight connections are performed during the ISS 3A Mission. The same tray is then deployed to allow connections of Z1 Truss to the Laboratory Module during the ISS 5A mission that occurred over a year after the 3A mission. So the OOCT on Z1 Truss would be tested in two configurations that are described in more detail later in this paper, but a graphic on-orbit representation is shown in Fig. 2 – ISS 3A Mission and 5A Mission on-orbit configurations.
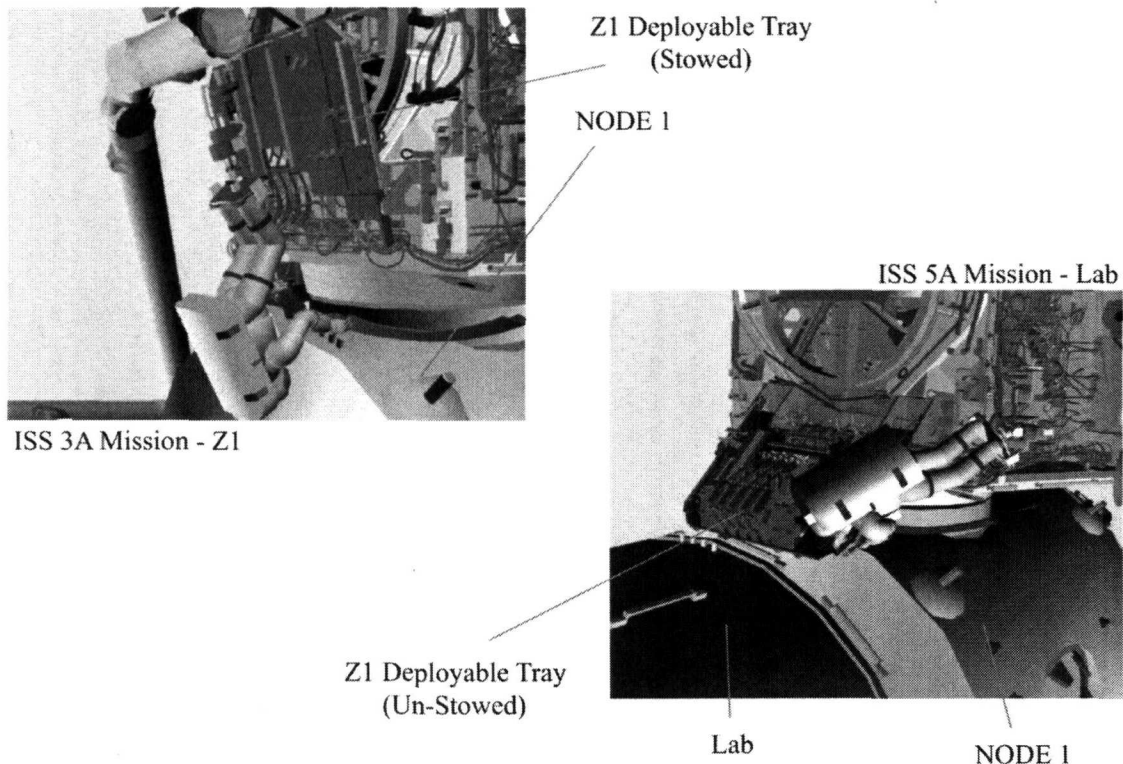
Z1/Node 1 & Z1/Lab On-Orbit EVA Interface

Figure 2. ISS 3A Mission and 5A Mission on-orbit configurations.

Once the on-orbit configuration was determined, the next step is, could the mated items be connected on the ground before launch. If the ground processing schedules overlapped and both items were at the Kennedy Space Center at the same time, then a flight-to-flight check could be done. Many ISS Elements were at KSC at the same time, unfortunately the design of the ground support equipment, containing the flight hardware, would not allow ISS Elements to physically mate together on the ground.

Another problem was the interfacings cable and fluid lines (sometimes called jumpers) that routed between the Elements would not be ready for both elements. The jumpers used for a future element were still being fabricated when the current element was launched. Because of these problems, the fit check would be performed first followed by the OOCT as shown in Fig. 1.

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There being no means to physically mate both flight hardware elements together, a Test Aid would have to be designed and built to substitute for one of the flight elements. This mostly was done for the element that would be launched first. The idea here is that first element, once on-orbit, can't really be modified (i.e. a "fixed" configuration), so a test aid would simulate the on-orbit element in the event any problems discovered during the OOCT, would be fixed on the future flight element and/or the jumpers still on the ground. The trick was how to get a high fidelity Test Aid built of the first element before it is launched. A number of techniques were used including:

- Flight hardware Interface Control Documents & Flight hardware drawings
- Photos of the flight hardware
- Direct physical mechanical measurements of the flight hardware and
- Digital Pre-Assembly (DPA) (electronic measurement of flight hardware to generate high accuracy digital model) of the flight hardware

Two different types of Test Aids were built, one to simulate EVA connections the second to simulate the ISS Common Berthing Mechanism (CBM) for IVA connections, shown in Fig. 3 - IVA Test Aid. Many other design & operational features were built into the Test Aid that included:

- Build IVA Test Aid CBM ring narrower than flight ring so it does not touch Flight Hardware
- Build a few rings to save cost
- Build feed though change out panels to allow multiple configurations of the few rings built
- Obtain flight-like connectors/fluid fittings to secure on test aid
- Model other adjacent flight hardware using Flight Hardware compatible foam
- Build test aid stand with high accurate X, Y & Z adjustments to allow high accuracy placement of test aids to simulate flight configuration. Use for both EVA and IVA OOCT's
- Build access way in test aids to give Astronauts a "hatch-like" view/orientation like they would see on-orbit
- Fabricate and assembly test aids in Florida to allow quick turn-around and repair of test aids, saving transportation cost as well, eliminated transportation to non-Florida location for work

Airlock to Node 1 Test Aid IVA OOCT
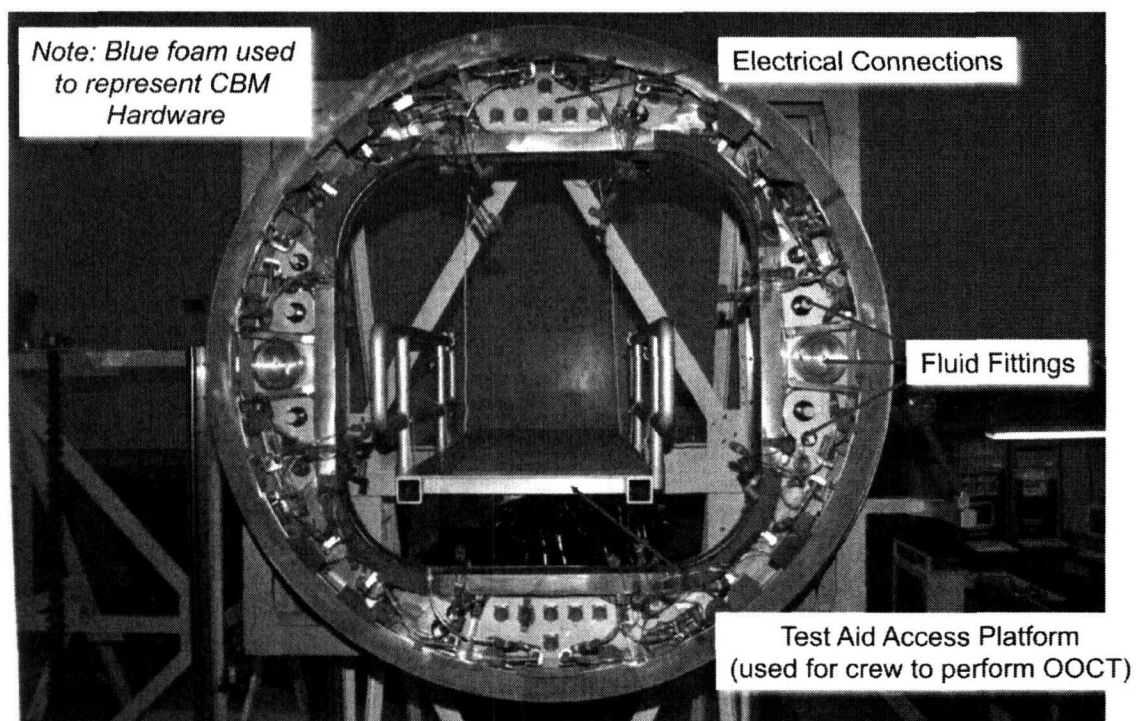
NODE 1 IVA Test Aid

Figure 3. IVA Test Aid. This Test Aid represented the ISS Node 1 Element and was used to perform an IVA OOCT with the flight Airlock. 4

VI. OOCT's PERFORMED ON ISS

Determining the flight configuration, understanding what flight hardware would be available, designing and building the Test Aid needed, then the next step was to bring a number of factors together in an integrated matter to then actually perform a fit check and/or OOCT. Ground processing of ISS Elements had begun many years earlier before the OOCT concept was created so trying to insert the OOCT into an existing schedule that was developed years earlier became one factor that was a serious problem. A main concern regarding the OOCT was if it would really simulate a flight configuration. To help alleviate this concern the fit check/OOCT would be performed as late as possible during the ground processing flow with the flight hardware in a final flight configuration to minimized any differences between the OOCT and how it eventually be configured on-orbit. Once the time period to perform the OOCT was established, getting the procedure and flight crew (using an EVA glove for EVA OOCT's) together with the flight hardware, test aid and ground processing team was a major integration effort. Everyone involved understood the criticality of the OOCT so great strides were made to achieve a successful OOCT.

As mentioned earlier, some of the first OOCT's planned were between the flight Z1 truss and a Node 1 Test Aid then a Lab Test Aid. Because two different on-orbit configurations were required for the Z1 Truss, two EVA OOCT's would be planned. To help consolidate logistics regarding two different configurations, two test aids were built and incorporated into one setup so both OOCT's could be performed with one test setup. Figure 4 – Flight Z1 Truss/Node 1 & Z1 Truss/Lab EVA OOCT, shows the actual test setup that was used for the OOCT's. The photo shown is the 3A mission configuration where the Z1 deployable tray was stowed to allow cable connections between Z1 and Node 1 test aid. The tray they would be lowered to perform the Z1 truss to Lab OOCT.
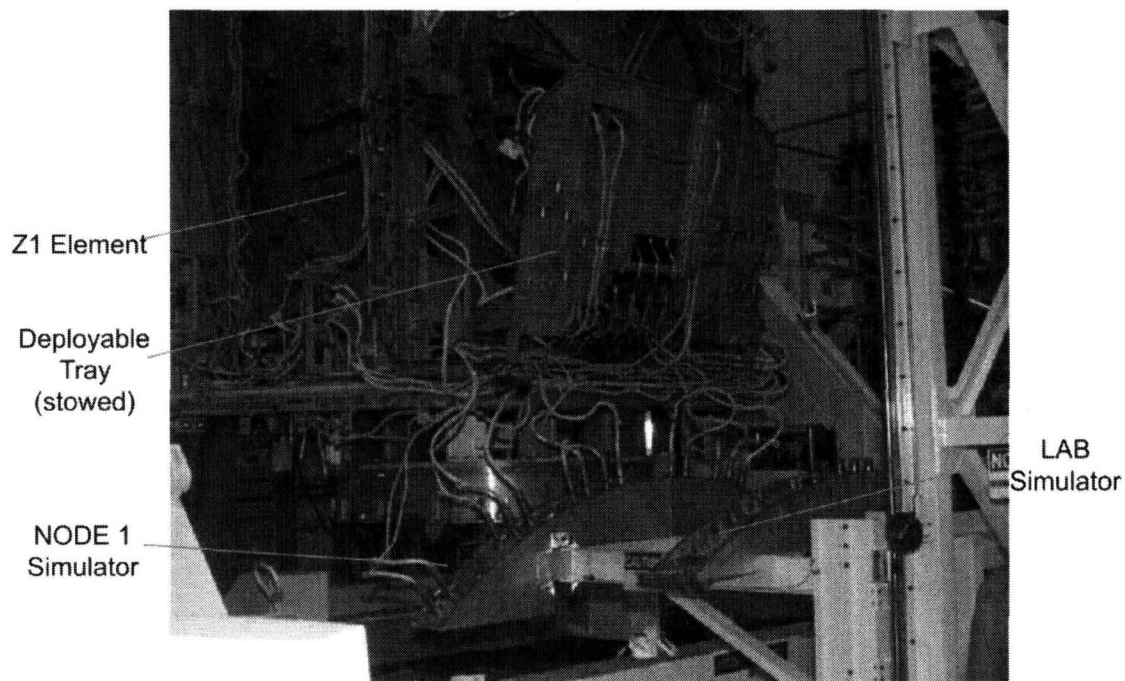
Z1/Node 1 & Z1/Lab EVA OOCT
Actual Hardware - SSPF Highbay

Figure 4. Flight Z1 Truss/Node 1 & Z1 Truss/Lab EVA OOCT

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Many problems were uncovered during these EVA OOCT's, some of which are shown in Fig. 5 - Problems found during Flight Z1 Truss/Node 1 & Z1 Truss/Lab EVA OOCT. A number of ideas were generated on how to fix the interferences, which then could be tested on the existing configuration to determine any success. Some of these were to move the connector up one slot; another was to rotate the connector away from the interference. A combination of both was the final solution as shown by Fig. 6 – Successful on-orbit mating of Z1 Truss to Node 1. Finding these interferences on the ground made fixes relatively easy as compared to what could have occurred on-orbit if the OOCT was not performed. Many EVA OOCT's were performed, some containing multiple elements in a very complex configuration as shown in Fig. 7 - Node 3, Lab, S0 Truss and Airlock EVA OOCT. The EVA OOCT's were very important because these represented tasks the crew would perform while in the EVA suit that had a time limit of about 8 hours, so problems discovered and fixed via the EVA OOCT's would save precious EVA time.

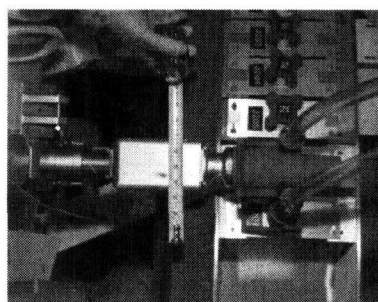Many Problems Discovered during
EVA Z1/Node 1 & Z1/Lab OOCT

Note: Blue foam used to represent adjacent flight hardware
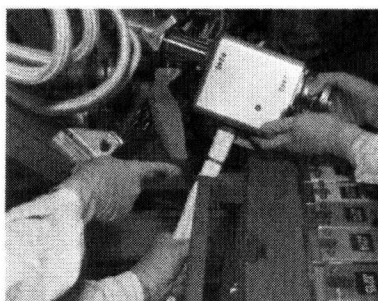
Circuit Interrupt Device (CID) #5
Interferes with handrail
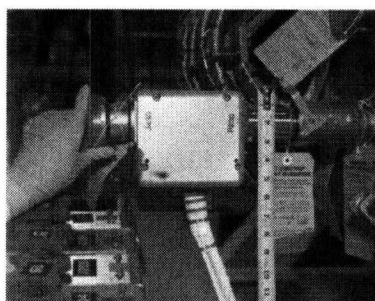
Circuit Interrupt Device (CID) #6
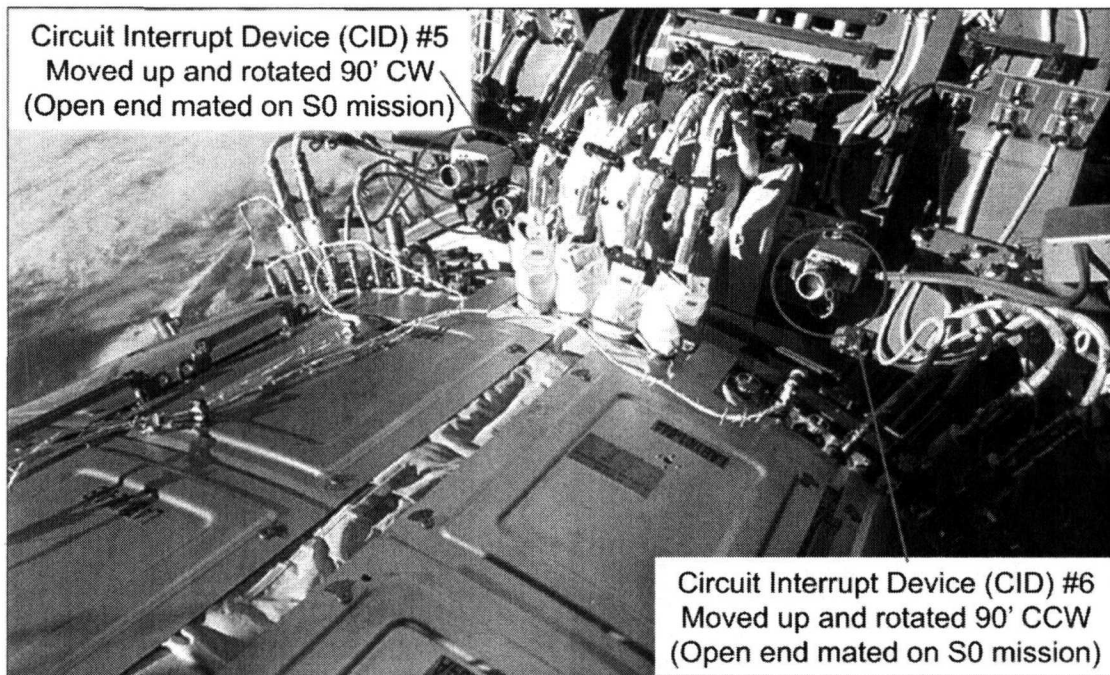Interferes with hard structure

Circuit Interrupt Device (CID) #6
Interferes with connectors
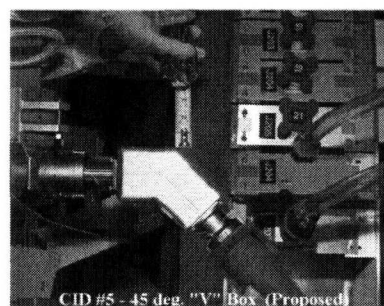
CID #5 - 45 deg. "V" Box (Proposed)

Propose fix, modify Circuit Interrupt Device

Figure 5. Problems found during Flight Z1 Truss/Node 1 & Z1 Truss/Lab EVA OOCT

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Successful Z1/Node 1 & Z1/Lab On-Orbit

Circuit Interrupt Device (CID) #5
Moved up and rotated 90' CW
(Open end mated on S0 mission)

Circuit Interrupt Device (CID) #6
Moved up and rotated 90' CCW
(Open end mated on S0 mission)

Note: This location was known as the "Rats Nest" do the fact that umbilical's from Node 1, Z1, Lab and SO Truss all came together in one congested area.

Figure 6. Successful on-orbit mating of Z1 Truss to Node 1

Node 3 Flight Umbilical to
Node 3/Lab/SO Truss Test Aid EVA OOCT

Airlock with gas tank Test aid

NODE 3 Test Aid

S0 Truss to Node 3 Flight Umbilical

SO truss Test Aid

Lab with Trunnion Pin Test Aid

Close-up of S0 Truss to Node 3
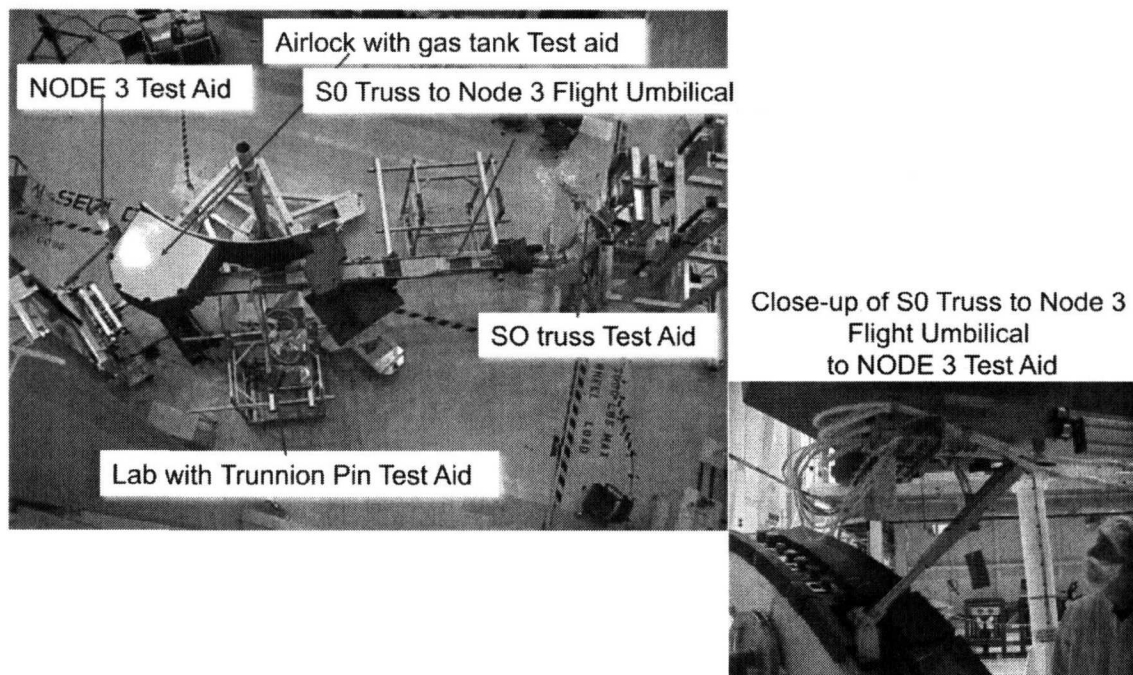Flight Umbilical
to NODE 3 Test Aid

Figure 7. Node 3, Lab, S0 Truss and Airlock EVA OOCT.

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The IVA on-orbit operations, whereas not as time critical as the EVA on-orbit operations, still represented a major step that needed to be accomplished to assure mission success. Many IVA OOCT's were performed between the major ISS Pressurized Elements, but in this paper, only the Node 1 Test Aid to Flight Airlock IVA OOCT's will be presented. Positioning the IVA Test Aid, shown in Fig. 3, into the proper orientation to represent the on-orbit configuration, proved very challenging. Figure 8 – Flight Airlock to Node 1 Test Aid IVA OOCT, depicts the configuration of the hardware used to perform the test.
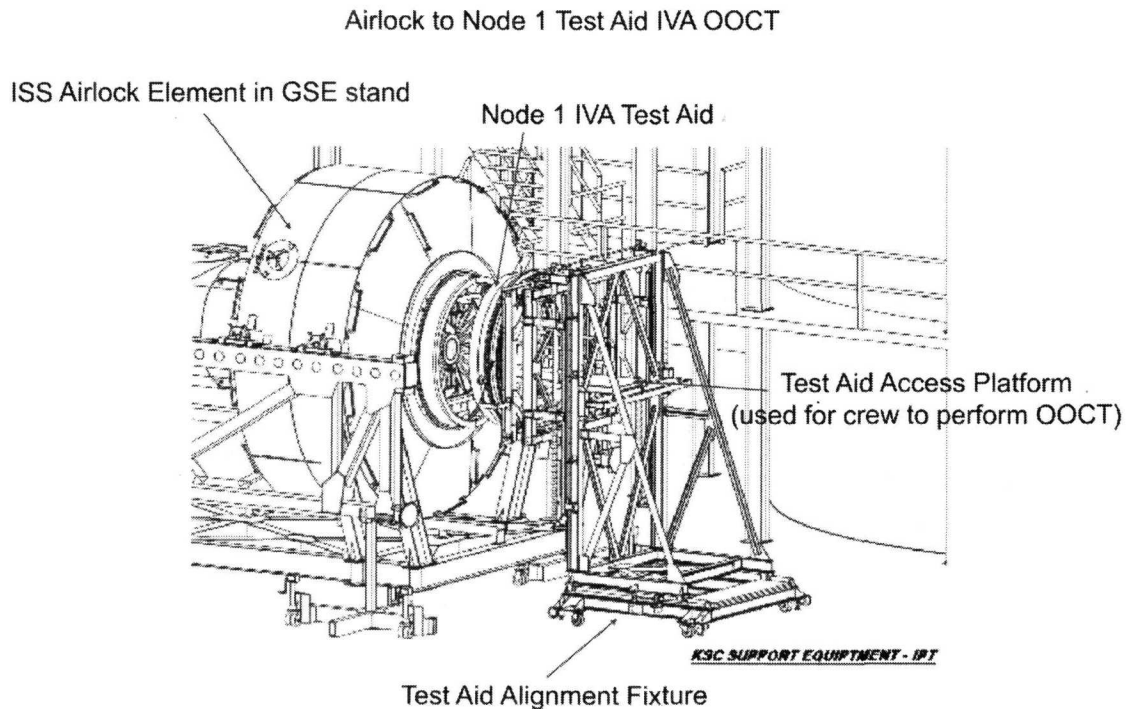
Airlock to Node 1 Test Aid IVA OOCT

Figure 8. Flight Airlock to Node 1 Test Aid IVA OOCT

Figure 9 – IVA fluid and ventilation jumpers between Flight Airlock and Node 1 Test Aid, shows how the complex criss-cross hardware configuration and the short length of the one jumper that if not found until on-orbit could have been a major setback to Airlock Mission operations. The jumpers were modified and a follow-on IVA OOCT was performed to verify the modification fixed the problem. This same scenario occurred during many IVA OOCT's where a problem was discovered, the hardware modified and retest performed to verify proper operations.

Some of those other problems encountered are shown in Fig. 10 – Other IVA problems discovered during IVA OOCT's and Fig. 11 – Fluid Fitting Torque Device and application to Gamah Fluid Fittings, showing a tool required to torque the Gamah flight fittings on fluid jumpers that routed between ISS Elements.

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Problem found during Airlock to NODE 1
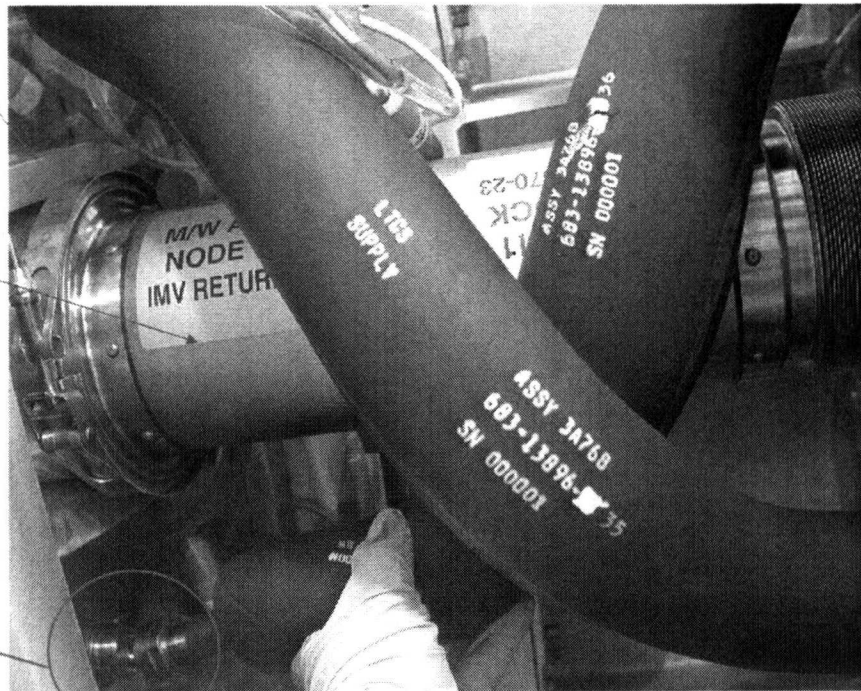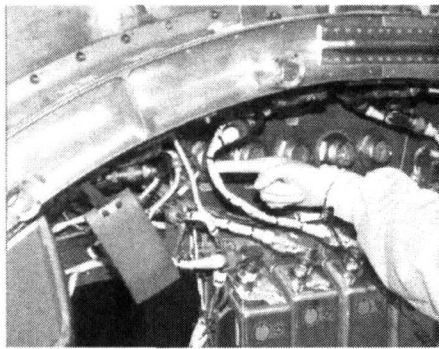Test Aid IVA OOCT
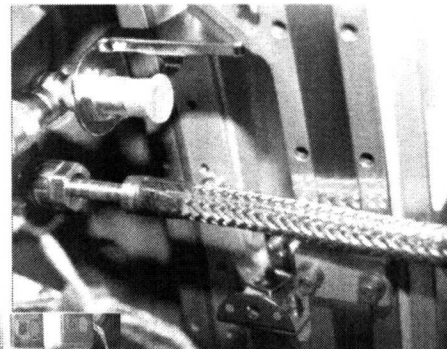

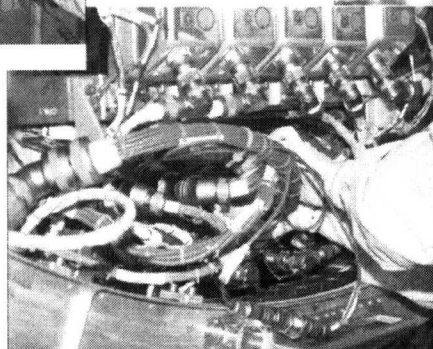Figure 9. IVA fluid and ventilation jumpers between Flight Airlock and Node 1 Test Aid
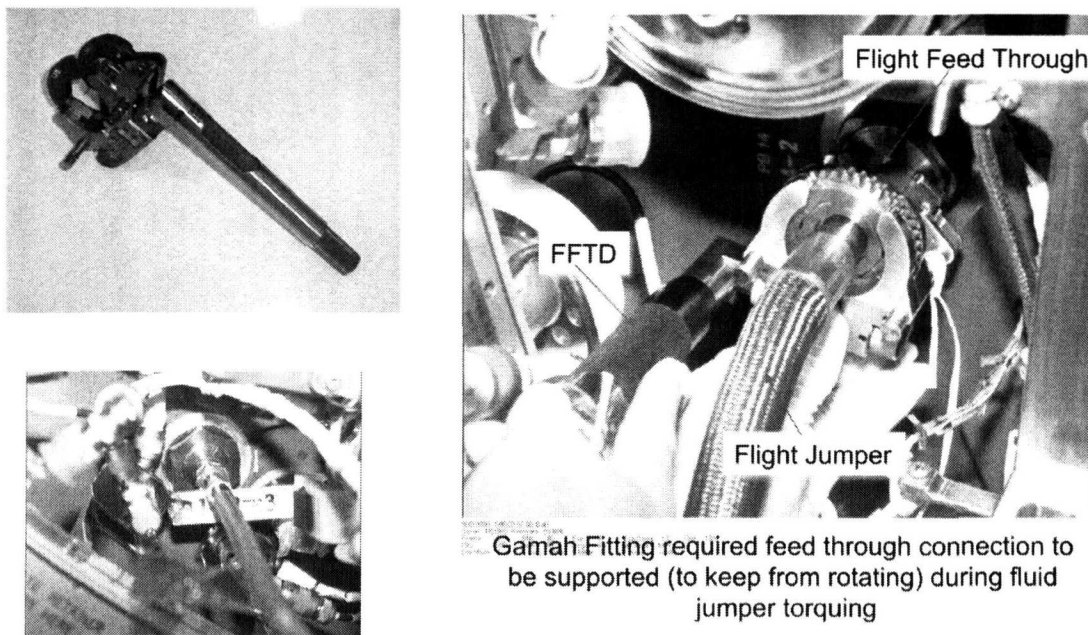
Problems found during other IVA OOCT's

Figure 10. Other IVA problems discovered during IVA OOCT's.

Gamah Fitting Tool - IVA Fitcheck/OOCT
Fluid Fitting Torque Device (FFTD)

Gamah Fitting required feed through connection to be supported (to keep from rotating) during fluid jumper torquing

Clearance problem that won't allow tool to fit onto Gamah Fitting feed through connection

Figure 11. Fluid Fitting Torque Device and application to Gamah Fluid Fittings

VII. LESSONS LEARNED

The OOCT's were performed on a variety of different hardware for different missions in different configurations that were required to assemble ISS Elements in Earth Orbit. Due to this wide range of applications, many lessons were learned, most of which are documented below:

- Design Flight Hardware and supporting GSE to allow physical mating of flight hardware elements together that are on the ground at the same point in time. By providing clearance on each end of the Element, while in its GSE stand, this could allow both elements to be mated in a flight-to-flight configuration eliminating the need for an OOCT for elements that are on the ground together.
- It is critical that the flight hardware is in the final flight configuration. Changes that would occur after the OOCT's can cause problems that could have prevented a successful mission.
- Piggyback on Integrated Testing. Flight jumpers are used for test, so build test aids to support free end of flight jumpers which would satisfy OOCT's'. Then connect test GSE cable to the backside of the Test Aid Connectors. Example shown in Fig. 14 – Piggyback OOCT onto Surface System Integrated Testing.
- ISS Test Aids designed with change out panels. This limits the number of rings built, are easy to reconfigure between OOCT's and the panels can be maintained in "flight configuration" for specific missions
- Design, fabricate and assembly test aids in Florida to allow quick turn-around and repair of test aids. Storing the Test Aids near the flight hardware kept the integration of logistics to a minimum while providing the best and quickest support towards the OOCT's process.
- Early purchase of flight connectors as well as design and build of flight jumpers is mandatory so future hardware would be ready for near term testing. This was a big problem for ISS where some OOCT's had to be performed with connector shells containing no pins due to long lead-time to obtain the flight hardware to configure the hardware properly.
- Flight Crew needs to be involved to get familiar with Flight Hardware and On-Orbit/Surface Operations. Flight Procedures were also verified, modified due to problems discovered during the OOCT's and some flight procedures were generated during OOCT.

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- Work Authorization Document (WAD) should have NASA KSC signature authority and task leader responsibility or designate Local Contractor as task leader. This will take advantage of local flight hardware processing expertise as well as having a task leader who is familiar with KSC ground processing operations.
- Plan early for CxP OOCT's and incorporate into Milestone schedules, to allow enough time to obtain hardware required, budget for personnel & equipment, prepare pre-integration tasks and successfully perform the OOCT's in the best possible environment.
- Other OOCT's lessons learned can be found at: http://www.nasa.gov/offices/oce/llis/1216.html

VIII. POSSIBLE APPLICATIONS TO CONSTELLATION PROGRAM

As of the writing of this paper, the Constellation Program Elements are still in the concept/design phase, so now would be the time to begin planning for Constellation fit checks and OOCT's. Taking the lessons learned from ISS and applying them during these early phases of the Constellation Program will avoid future problems and save money associated with last minute changes or trying to incorporate a new process into a future existing processing flow.

Figure 12 – Possible Constellation Lunar Surface and Lunar Orbit Element, are concepts of what a future Lunar Orbit support system and Lunar Surface System configuration may look like. Below are a listing of some possible OOCT applications for Constellation EVA & IVA operations:

- ISS On-Orbit Operations
  - Orion to ISS Interface
- Earth and Moon On-orbit Operations
  - Orion to Lunar Surface Acquisition Module (LSAM)
  - Hardware in Lunar Orbit
- Surface Operations (Moon & Mars)
  - Surface Habitation Element to Element
  - Surface Extended Surface Element to Surface Carrier Element
  - Surface Rover to Habitation Element
  - Surface Science Packages to Required Interface
  - EVA Suit to Habitation Element
  - EVA Tools

OOCT Applied to Constellation Program
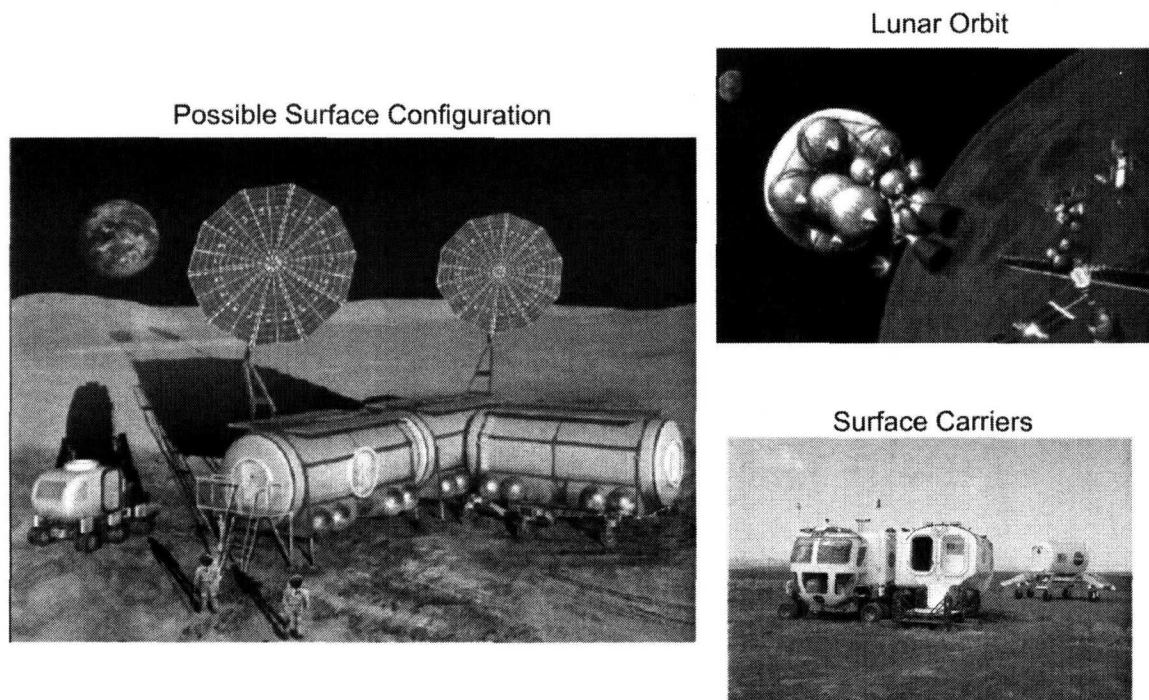(Rename to Surface Systems Constraints Test SSCT)

Lunar Orbit

Possible Surface Configuration

Surface Carriers

Figure 12. Possible Constellation Lunar Surface and Lunar Orbit Element

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Based on these initial concepts, using lessons learned from ISS and renaming OOCT to Surface Systems Constraints Test (SSCT) so it applies to Lunar and Mars surface operations, Fig. 13 – Constellation Fit Check & Surface Systems Constraints Test (SSCT) concepts are shown where "today" configuration checks the actual first piece of flight hardware (Hab 1) with the interface hardware connectors from the second piece of flight hardware (Hab 2). Then a Hab 1 interface simulator/test aid would be created before the flight Hab 1 is launched to the moon. This Hab 1 Test Aid is then fit checked against the flight Hab 2 when it arrives sometime in the future . This verifies that the proper spacing and orientation of the interface hardware is correct, thus testing the lunar configuration (Hab1 to Hab 2) on earth first to assure the hardware will assembly correctly once the second element reaches the moon. The example below shows direct hardware to hardware interface, the connections between the two element could be via umbilical's (cables and fluid lines) similar to how the ISS elements we connected. In that case the umbilical's are fit checked against Hab1 during the SSCT and then those same umbilical's are fit checked between the Hab 2 and Hab 1 test aid.

CxP Fit Check & SSCT Concept

"Today" - Fit check future Hab 2 connectors to Hab 1 flight Element

"X time in the future" - SSCT of Hab 2 Flight Element to Hab 1 test aid
(by default you get fit check to Hab 2, piggyback on testing so only connect to flight hardware one time)

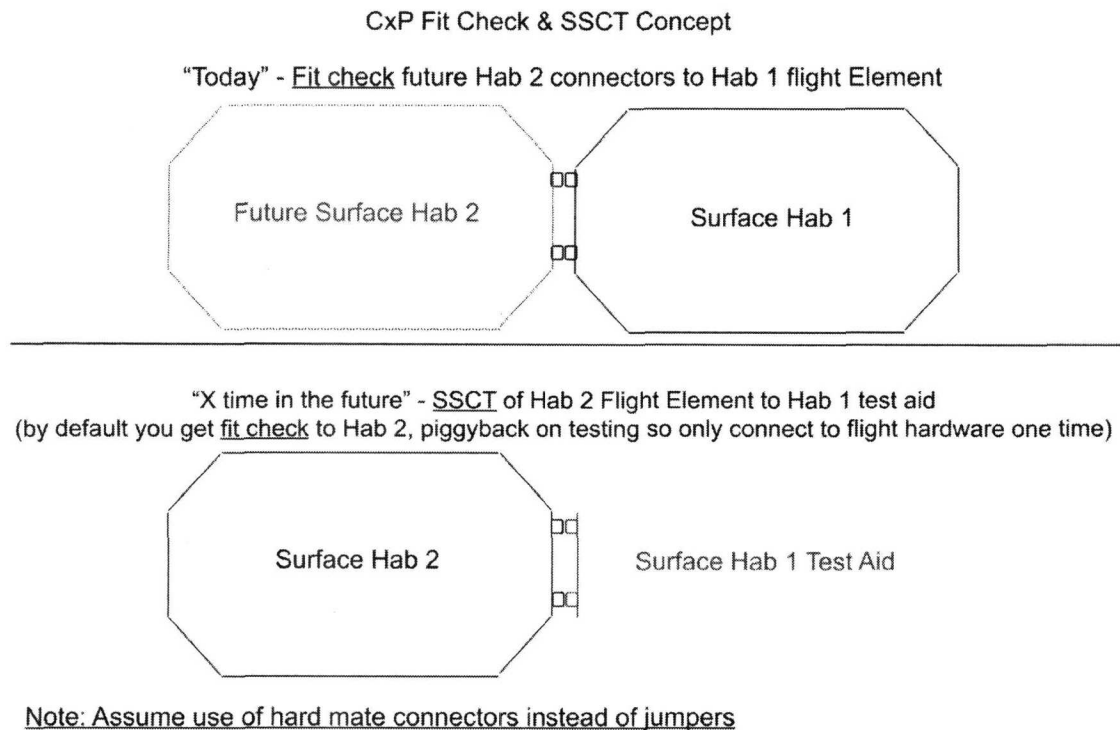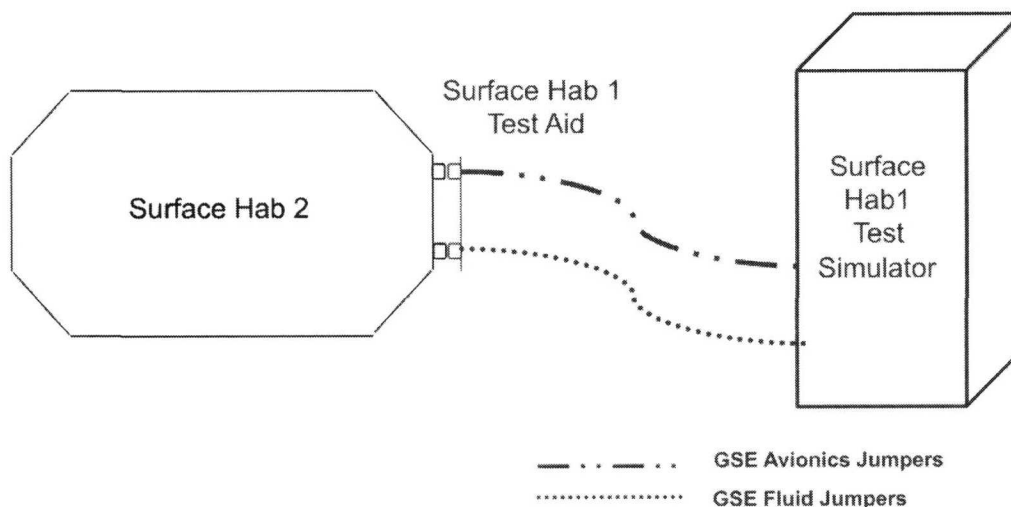Note: Assume use of hard mate connectors instead of jumpers

Figure 13. Fit Check & SSCT Concept for surface habitat elements

Figure 14 – Piggyback SSCT onto Surface System Integrated Testing, shows a possible configuration where a second surface module is being testing against a simulator of the surface element already on the moon. Planning for the GSE to be properly designed to allow an SSCT check, the backside of the test aid could be connected to the Surface Simulator, so the SSCT is accomplished (a physical check between elements) during setup for the functional test between elements. This same process then could be used for each additional Lunar Surface System Element and Lunar Orbit Elements.

An SSCT can also be performed against the surface carrier elements as represented by Fig. 15 - Fit check and SSCT concepts for surface carrier elements. The idea is to create a test aid representing the carrier so all future items that will interface with the carrier will go through an SSCT before they are launched.

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Example of SSCT Piggy-backed on Surface Hab 1 to Hab 2 Integrated Test

Surface Hab 2

Surface Hab 1
Test Aid

Surface
Hab1
Test
Simulator

— · · — · · GSE Avionics Jumpers
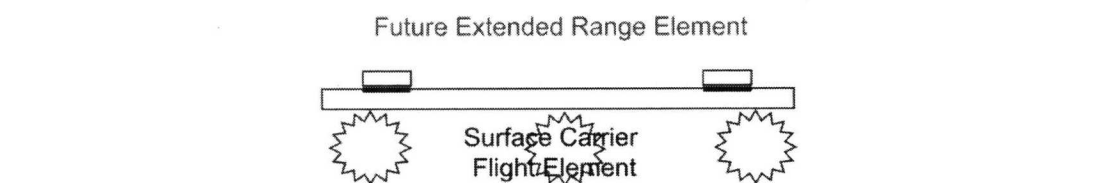
· · · · · · · · · · · · GSE Fluid Jumpers

Note: Assume use of hard mate connectors instead of jumpers

Figure 14. Piggyback SSCT onto Surface System Integrated Testing

CxP Fit Check & SSCT Concept

"Today" - Fit check future Extended Range Element connectors to Surface Carrier Flight
Element

Future Extended Range Element

Surface Carrier
Flight Element

"X time in the future" - SSCT of Extended Range Flight Element to Surface Carrier Test Aid
(by default you get fit check to Extended Range Element, piggyback on testing
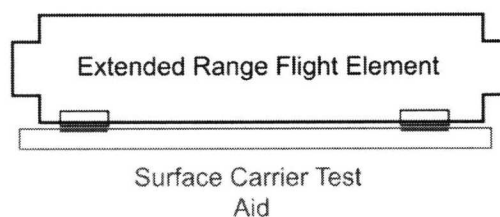so only connect to flight hardware one time)

Extended Range Flight Element

Surface Carrier Test
Aid

Figure 15. Fit check and SSCT concepts for surface carrier elements.

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IX. CONCLUSION

The OOCT concept used during the International Space Station uncovered a wide variety of problems and helped assure on-orbit successful assembly of the ISS Element's. Combination of configuring the flight hardware properly, participation of the Astronauts and performing a full dry run of on-orbit operations was the key to the OOCT process. Many missions were saved by performing the OOCT's, prevented a backlog and/or disruption in the ISS assembly sequence. The knowledge gained will be very helpful to assure the same successes for the Constellation Program. Planning needs to be performed early in the design phase to assure the flight hardware is prepared for future OOCT operations, the schedule contains the appropriate time line to perform the tests and the budget is established to fund all OOCT work. Appling the OOCT concept, now to be renamed SSCT, to near term Constellation missions should be performed with a long-term goal to continue the SSCT concept to Mars Surface Systems and beyond.

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X. BIOGRAPHY

Mr. Haddad holds a Bachelor of Science Degree in Mechanical & Aerospace Engineering and Masters of Science Degree in Industrial Engineering and Management Systems, both from the University of Central Florida. He began working NASA at Kennedy Space Center (KSC) as a mechanical and fluids engineer, assembling, modifying, servicing and testing of flight hardware for domestic and international payloads. He specialized in hypergolic propellants, and was responsible for ground processing flow for Shuttle planetary, observatory and satellite class payloads such as Galileo, Ulysses, Gamma Ray Observatory, TDRS communication satellites and Hubble Space Telescope. Mike performed a six-month detail assignment to Johnson Space Center in Houston, Texas, with responsibilities that included, flight console operations for STS-70 & 71 from the Mission Control Center, working Shuttle/Station upgrade activities and development of Space Station on-orbit operations concepts and requirements. He served as a senior systems engineer working International Space Station (ISS) with primary responsibilities that included Extra Vehicular Activities (EVA) as KSC Point-of-Contact for EVA & Crew Systems responsible for test, verification and on-orbit support of Space Station EVA systems. Mike was also an integration engineer for the ISS Multi-Element Integrated Testing (MEIT) performing requirements generation, test and verification activities. He was in the final selection group for the Astronaut Class of the 1998. Received the NASA Silver Snoopy Award in 2001 for work in EVA operations. Currently Mike is in the KSC Constellation Project Office working Systems Engineering and Integration with responsibilities that include generating Constellation requirements, participation in technical trade studies and KSC Point of Contact for EVA Systems and Lunar Surface Systems.